Title
A model driven question- answering system for a CAI environment

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A MODEL DRIVEN
QUESTION-ANSWERING SYSTEM
FOR A CAI ENVIRONMENT

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TABLE OF CONTENTS

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Introduction

An intriguing goal for a CAI system is the ability for it to perform as a general purpose question-answering system. Several years ago Jaime Carbonell at M.I.T. commenced an ambitious research project to investigate the feasibility of such a system (1). His goal was to create a Mixed Initiative CAI system which would permit the student to interrupt the tutorial process and pose direct questions. Although Carbonell's system performed quite well with highly structured geographic data, its direct application to less uniformly structured data seemed problematic. The inferencing techniques used were clearly tuned to answering static and simple factual questions. Nevertheless, the philosophy underlying the Mixed Initiative system remains impressive.

Our goal was to design a question-answering system suitable for use in a learning situation to work with dynamic material as well as static. Such a system should allow good representation of processes, their interactions, and through these, be able to deal with causality. The notion of causality is central to the characterization of all physical phenomena. It also underlies much of our common sense knowledge of the world and for this reason, if no other, deserves close study.

Meteorology provides an ideal body of knowledge for studying these problems. Introductory meteorology is characterized by the study of the processes of evaporation, condensation, cloud formation, precipitation, etc. and their effects upon each other. These processes are amenable to a general representation in a qualitative manner. To explain the processes which cause rain, for example, lengthy logical explanations can be offered which need not be preponderantly quantitative. There do exist, of course, complex numeric treatments of topics in meteorology, but much of the introductory material can be represented with variables and functions which assume a purely directional nature. Thus, it is possible to talk about the relative behavior of meteorological entities without having to solve differential equations in an attempt to determine precise relationships.

In constructing its replies, we expected our system to generate qualitative statements and not simply to regurgitate numeric solutions. We did expect, however, that if the student asked a quantitative question, the response generated by the system would be a qualitative explanation coupled with a sequence of numeric computations. Also, we recognized that if our question-answering system was to be useful in a CAI environment, it would have to respond not only to "What happens" but also to "Why does it happen" questions. (Examples of questions will be covered in detail in a later section.)

In addition to being able to handle these kinds of questions, we required that our system not only be generalizable to other areas of knowledge, but that it also incorporate a representation of information (inference rules, etc.) that would facilitate the addition of new concepts as well as new facts.

In view of these goals, we rejected the highly popular approach which invokes resolution type strategies which require an axiomatic representation of its knowledge about the world. Although such systems are extremely attractive because of their generality, this benefit is more than offset by:

1) The degree of difficulty in obtaining a complete axiomatic characterization of a body of knowledge as complicated as even the minor subset of meteorology under consideration;

2) The substantial complications involved in the handling of causality which often requires complex considerations of the current "state of the world".

On the other hand, we did not want to construct a system so specialized that it would not be applicable to any other areas of knowledge. The following sections discuss a question-answering system that satisfies these basic requirements. The system is written in LISP 1.6 for the PDP-10 and occupies approximately sixty-thousand words of core.

Representation of Processes

Whereas most question-answering systems excel in their ability to perform fact-retrieval tasks or answer true-false type questions, our system has been designed with broader goals in mind. Central to meteorology is the notion of a "process" (cloud formation, hail formation, evaporation, etc.). We are therefore much concerned with efficient ways of encoding information about processes. Although the structure of processes can be characterized by statements in a predicate calculus, we have sought a representation by which processes could be more naturally "understood" by the computer. An obvious possibility is to represent each process by a procedure - the "meaning" of the process could then be realized by evaluating the procedure. Such a representation of a process has certain advantages but, on the other hand, provides very little structural framework for specifying interactions among processes. (Winograd's (4) use of PLANNER might be an exception.)

Since comprehension of a process often emerges through studying its effects or interactions with other processes, and not by studying the process in isolation, this unconstrained representation was not pursued. Instead, a compromise was sought in which the computer could symbolically execute a process and in which the interactions among various processes could be made perfectly explicit. (These interactions, as will be discussed later, function as the basic set of inference rules for this system.)

Borrowing from automata theory, we decided to represent each process as an automaton where each automaton is itself represented as an augmented state transition table (as shown in TABLE 1 on the following page). Each row in the transition table concerns a particular transition between two states in that automaton. The first column specifies the particular transition between two given states. The second column specifies conditions which must be satisfied over the global or external state of the system before the transition can occur. The column marked "Internal Conditions" specifies constraints concerning which states other automata must be in before this automaton could exercise the given transition. Both the external and internal constraints take the form of LISP predicates which must evaluate to "True" before the transition can occur.

TABLE 1

TRANSITION TABLE FOR AUTOMATON

AUTOMATON	TRANSITION	EXTERNAL * CONDITIONS	INTERNAL * CONDITIONS	* COMPUTATION	ASSOCIATED PHRASE
AIR-WATER PROCESS	B => A	-	[IIB]=A OR [IB]=C	-	NET EVAPORATION
	B => C	-	[IIB]=C OR [IB]=A	-	NET CONDENSATION
	A => B	-	[IIB]=C	-	EQUILIBRIUM
	C => B	-	[IIB]=A	-	EQUILIBRIUM
RATE OF EVAPORATION	B => A	[N]=X => [N]=B (X # B)	[WT]=A	IF NB="TRUE" THEN IB=.85 x TABLE(WT) ELSE IB=TABLE(WT)	DECREASE
	B => C	[N]=B => [N]=X (X # B)	[WT]=C	-	INCREASE

The first line is read: "A state of Equilibrium becomes a state of Net Evaporation if either the Rate of Condensation decreases or the Rate of Evaporation increases". The other symbols used are: [N] for the state of Nuclei(see TABLE 2) and [WT] for the Water Temperature automaton (see Appendix 4).

* These columns are arbitrary LISP predicates.

Usually, these predicates are simple Boolean functions. They can be, however, as complicated as is necessary to capture the subtleties of interactions between two given concepts or processes of the transitional system.

The "Computational Column" specifies how a parameter of the automaton is to be computed if the query requires a numeric answer. This entry is either the name of a table or the name of a computational procedure along with information specifying the binding of arguments for this procedure. The last column, "Text Generation", specifies a fragment of text that can be generated in conjunction with the automaton making this transition. We will later see how these fragments can be synthesized into a paragraph or complex sentence in response to a complex "Why" question.

The cross product of all these automata (one for each process or concept) forms a global automaton which functions as the dynamic model of our meteorology data base. (See Appendix 4 for a synopsis of the sub-automata that currently form the global automaton.) The user can easily augment this global automaton by adding new sub-automata and specifying via the internal and external conditions (columns) how the new automata interface with the old. The user can, in fact, throw out the entire Meteorology global automaton substituting his own (on say ecology) and thereby redefine the subject matter of the system. In this respect, the system's data base is table-driven.

Representation of Factual Information

Not all "knowledge" can be conveniently encoded in terms of automata. We therefore needed another specialized data structure to represent the kind of information we believed important to meteorology but which was not easily captured by the above methods. In addition, certain information about "processes" (e.g., their definition) is inherently factual, rather than functional, and hence could be best represented external to the transition tables. In light of these considerations, a semantic/conceptual network, similar to those developed by R. Quillian (2) and R. Simmons (3), was designed. Our network possesses three basic kinds of nodes, each with slightly different property list structures. Since any node within a given generic class has the same kind of properties, we can take advantage of this uniformity in writing specialized routines to perform a limited class of inferences. Nevertheless, this network along with its procedures for performing inferences, does not have the flexibility of a general purpose question-answering system. In order to expand the range of questions that the system can handle, the user must adjoin new inferencing procedures to the executive which processes this network.

The three kinds of nodes in this semantic/conceptual network are:

1) Objects (e.g. Rain, Ice, Snow, ...)
2) Concepts (e.g. Temperature, Pressure, Freezing Point, ...)
3) Processes (e.g. Evaporation, Precipitation, Saturation, ...)

Objects are interrelated by two basic ordering relationships; e.g., x "is a kind of" y, or x "is an example of" y. These relations induce a partial ordering over the set of objects and function in the standard way by allowing the object x to inherit properties of the object y as specified by the given inference procedures. Each object has the following properties (a property can have sub-properties):

1) DEF: an ASCII string giving the object's definition - key words in the string are subject to cross-referencing as described later.
2) PATT: Physical attributes, such as shape, size (bounds), color, weight, etc.
3) BC: Boundary conditions for the object's

a) formation
and b) existence.

4) SUB: What things are examples of this object.

5) EX: What things this object is an example of.

6) LOC: Where the objects are usually found or contained.

7) WAFF: What things the object affects (which process automata this object affects)

8) UF: What things the object is used for. (Which process automata this object is involved in)

9) WAFFT: What affects the object's attributes.

10) TXT: A short exposition (coded simply as text) about this object.

11) SCH: A schema used by the CAI executive to specify an ordering over the other properties for "Tell me something about x" type questions.

12) XREF: Contains cross-reference information

13) SYN: Any synonyms that are also contained in the network

The network structure for processes has various properties in common with the structure for objects. There are, however, important differences as seen by examining the property list for processes:

1) INV: Inverse of this process.

2) XFORM: The given process transforms object (state) x into object (state) y.

3) EX: Examples of the process.

4) BC: Boundary conditions (same as for the objects).

5) DEF: (Same as for the objects.)

6) SYN: Technical synonyms for this process that are not already contained in our lexicon.

7) EXP: (Each process node has a corresponding automaton. This property list contains simple explanations for each possible transition in that automaton. These explanations are at present simply ASCII strings and do not cross-reference any other part of the network.)

8) XREF: contains cross-reference information.

Conceptual nodes have only one additional property which specifies (if applicable) the units of measurement for that concept.

The most important property that all three nodes have in common is the "XREF" property which specifies for every "node" in the semantic/conceptual network which other nodes contain properties which reference (mention) this node _and_ in which property this reference occurred. Therefore, when a procedure commences its search from a particular node, it can selectively pursue certain paths determined by how this particular node is used or referenced by other nodes.

Question-Answering

Having discussed the two basic representations of information in our data base, we are now in a position to discuss how question-answering is performed. We will draw heavily upon examples to elucidate the inferencing techniques fundamental to our system.

Students using this system invariably formulate questions assuming certain contextual information that they have just been presented. Questions are not formulated in a vacuum, and almost always involve numerous presuppositions even apart from contextual considerations. For example, if a student asks: "What happens when the temperature drops?", he undoubtedly is presupposing that the temperature is already above absolute zero (obviously), that there is some water vapor present or perhaps some other objects whose states might be altered. In certain contexts, it would be clear in what range the temperature was before it "dropped". Or, depending on previous assertions, students may be assuming that temperature means "air temperature" and presupposing that air temperature is always equal to the water temperature (of the water droplets in the clouds). One characteristic of either contextual or presuppositional knowledge is that it is implicit and therefore it would be unreasonable to expect students to make all such assertions explicit. A useful system (in a CAI environment) must somehow keep track of at least some of these underlying assumptions. In other words, a "model" of the student (albeit simple) must be kept up-to-date with respect to his current assumptions.

Towards this end, an external (or environmental) state vector E is formulated, which reflects the student's current assumptions. In essence, E is a sequence of flags and parameters which are altered in accordance with the kind of material the student is currently exploring. TABLE 2 specifies the parameters included in the vector representing the E state. These parameters are primarily referenced by the predicates in the "External Condition" columns of the transition tables (TABLE 1). In the absence of any information, default conditions are specified which are set to evoke the maximum information from the model. For example, if the student is working with clouds, the clouds are assumed to be deep and condensation nuclei are assumed to be present. These conditions are necessary for the formation of precipitation. When a student lowers the air temperature, the precipation process starts. The response generated explicitly states these assumptions (see Appendix 3). At this point the student sees what assumptions have been made and can ask "Suppose there were no condensation nuclei?".

To best illustrate how the process model performs

TABLE 2

EXTERNAL STATE VECTOR
(* INDICATES DEFAULT VALUE)

[S] (WATER TEMPERATURE ALWAYS EQUALS AIR TEMPERATURE)
* T = "TRUE"(ALWAYS TRUE WHEN DEALING WITH WATER IN A CLOUD)
F = "FALSE"

[N] (NUCLEI)
A = "NON-HYGROSCOPIC NUCLEI PRESENT"
* B = "HYGROSCOPIC NUCLEI PRESENT"
C = "NO SURFACES OR NUCLEI PRESENT"
D = "SURFACES PRESENT"

[G] (GRADIENT OF CHANGE)
A = "GRADUAL"
* B = "SUDDEN"

[C] (CLOUD DEPTH)
* D = "DEEP"
S = "SHALLOW"

[E] (SUFFICIENT ELECTRICAL FIELD PRESENT)
* T = "TRUE"
F = "FALSE"

[IC] (ICE CRYSTALS PRESENT)
* T = "TRUE"
F = "FALSE"(CAN BE MADE TRUE BY THE CLOUD FREEZING PROCESS)

[SCWD] (SUPER-COOLED WATER DROPLETS PRESENT)
T = "TRUE"
* F = "FALSE"(IS MADE TRUE BY CONDENSATION OCCURRING BELOW ZERO DEGREES)

[NWD] (NORMAL WATER DROPLETS PRESENT)
T = "TRUE"
* F = "FALSE"(IS MADE TRUE BY CONDENSATION OCCURRING ABOVE ZERO DEGREES)

[FN] (FREEZING NUCLEI PRESENT)
* T = "TRUE"
F = "FALSE"

TABLE 2 (CONTINUED)

EXTERNAL STATE VECTOR

[T] (TURBULENCE EXISTS)
* T = "TRUE"
F = "FALSE"

[P] (PROCESS TYPE)
* C = "CONTAINER"
M = "METEOROLOGICAL"

[D] (DUALITY OF PROCESS POSSIBILITY)
T = "TRUE"
* F = "FALSE"

[ATLA] (AIR TEMPERATURE AT LOWER ALTITUDES)
H = "GREATER THAN 20 C"
W = "GREATER THAN 0 C"
C = "LESS THAN 0 C"
* X = "UNSPECIFIED"

PHYSICAL PARAMETER DEFAULT VALUES

AIR TEMPERATURE = 25 DEGREES CENTIGRADE
WATER TEMPERATURE = 25 DEGREES CENTIGRADE
BAROMETRIC PRESSURE = 760 MM OF MERCURY

question-answering, let us consider the following question:

Q: "What happens when the water temperature decreases?"
(For actual system response see page 20)

The cross product or global automaton is set to its initial state and the E (external) state is likewise set. The question is parsed, interpreted and a command is established to "twitch" the global automaton by forcing changes in the E state or by forcing a particular transition in one of the sub-automata. In this case that automaton representing temperature is forced from the stable state (B) to the decreasing state (C). Once an internal state (a state of one of the automata making up the global automaton) is altered, the relevant predicates (as determined by cross-reference) in the other automata are evaluated to see if their respective automaton can exercise a transition. This process is repeated recursively until no new transitions occur.

What develops is a tree reflecting all possible global state changes where any single transition of the global automaton reflects one and only one transition of a sub-automaton. If a condition is achieved in which more than one sub-automaton could exercise a transition, then from that global state a branch point develops (of the above-mentioned tree) - one branch for each sub-automaton that could currently effect a transition. At each of these points, there is a problem of which branch to expand first and in fact whether to use a depth first or a breadth first expansion. As long as the various branches are independent (i.e. if no automaton transition requires conditions from both branches), there is no difference in the resulting trees. As soon as one of the transitions requires conditions from more than one branch, it can make a difference how the tree is expanded. To help with this problem, certain timing information is contained in particular transitions. This information is currently of the form "don't expand this node any further until all other nodes have been expanded". It is used to unfold the tree in a way dependent upon the processes involved and avoids the arbitrariness of a breadth or depth first approach.

The resulting tree acts as a "deep structure" for the generation of the explicative sentences or paragraphs which form the response to the query. The timing information is retained in the tree and provides natural break points in this response. At this stage only the crudest text generator is invoked, as can easily be seen by examining the sample output. Nevertheless one can see that enough information is present to permit reasonable text generation.

(The words surrounded by parentheses in these examples are lifted directly from the "text" column in the appropriate transition table.)

If the question had been a true-false type question such as "Does Relative Humidity decrease when the temperature drops?" this tree would be searched for a node (global state) that corresponds to a decrease of the Relative Humidity automaton. However, a special situation arises when a single non-terminal state is used to verify the correctness of the answer. For example, both of the following questions are answered "True" (in a contained environment):

1) Does the Relative Humidity increase with a drop in temperature?

2) Does the Relative Humidity decrease with a drop in temperature?

Although our system answers "True" to both questions, this situation is not paradoxical since the contextual information (as generated by a global state transition) is altered between when question 1 gets an affirmative response and when question 2 gets an affirmative response. [For more examples of questions of this form, we refer the reader to Appendix 1.]

Handling "Why" type questions follows directly from the above consideration. In terms of the above example question, suppose we asked:

> "Why does the Rate of Condensation decrease when the water temperature decreases?"

To answer this question we need simply scan the above mentioned tree to find a node which reflects the appropriate transition of the Rate of Evaporation automaton and then construct a response from the chain arising from pursuing a path from the root of the tree to that node.

There is one obvious case where this strategy fails. Suppose the node being sought is adjacent to the root of the tree. In this case, no information is gained from the chain. When this happens, the semantic/conceptual network is accessed for explanatory information on that particular transition. This information may be a simple explanatory note or in special cases, another automaton. This automaton can be used to generate the explanatory note and may be investigated further by the student. For example, if the student wants to know why the Rate of Evaporation increases when the Water Temperature increases (see TABLE 1 for condition), an automaton model of thermo-dynamics and molecular interactions could be called upon to explain this transition. After explanation of the transition, the molecular model is available if the student wishes to continue his investigation along these lines. In this way hierarchies of automaton models can be created for exploration by the student.

Because the generated tree is preserved until the next question is posed, the following type of dialog is always possible:

> Q: Does x cause y to happen?
> R: Yes.
> Q: Why?
> R: Because ...

In addition to these purely qualitative questions, quantitative queries can be likewise handled. Suppose, instead of asking the qualitative question:

> Q: What happens when the Water Temperature drops?

We ask the question:

> Q: (What happens when the Water Temperature drops to 22 degrees)
>
> R: THE (AIR TEMPERATURE) (DECREASE) FROM 25 TO 22 DEGREES BECAUSE (WATER TEMPERATURE) (DECREASE). THE (HUMIDITY OF SATURATION) (DECREASE) FROM 24 TO 20 MM HG BECAUSE (AIR TEMPERATURE) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (RELATIVE HUMIDITY) (INCREASE) FROM 100 TO 120 % BECAUSE (HUMIDITY OF SATURATION) (DECREASE). THE (RATE OF EVAPORATION) (DECREASE) FROM 24 TO 20 MM HG BECAUSE (WATER TEMPERATURE) (DECREASE).

```
THEN THE (AIR CONDITION) (SUPERSATURATED) BECAUSE (RATE
OF  EVAPORATION)  (DECREASE)  AND  (GRADIENT OF CHANGE)
(SUDDEN).   THE  (PROCESS)  (NET  CONDENSATION) BECAUSE
(RATE    OF    EVAPORATION)    (DECREASE)    AND    (NUCLEI)
(HYGROSCOPIC   NUCLEI    ARE    PRESENT).    THE  (ABSOLUTE
HUMIDITY)  (DECREASE)  FROM  24  TO  20  MM  HG BECAUSE
(PROCESS)  (NET CONDENSATION), THE (RELATIVE HUMIDITY)
(DECREASE)   FROM  120   TO  100  %  BECAUSE  (ABSOLUTE
HUMIDITY) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN).
THE  (RATE OF CONDENSATION) (DECREASE) FROM 24 TO 20 MM
HG BECAUSE  (ABSOLUTE HUMIDITY)  (DECREASE).   THE (AIR
CONDITION)  (SATURATED)  BECAUSE (RATE OF CONDENSATION)
(DECREASE).

THEN  THE  (PROCESS)  (EQUILIBRIUM)  BECAUSE  (RATE  OF
CONDENSATION) (DECREASE).
```

Again, the constructed response is open to further interrogation by the student. For example, he might ask how we arrived at the value for the Humidity of Saturation of 20 mm. Hg. For such a request we would access that column of the appropriate transition table and see what technique is used for that particular computation. If it is a table look-up, then the student can request the table to be printed. If it is a procedure, then the student could ask to have the formula displayed, to insert his own values into the procedure or have a graph drawn of the functional values produced by the procedure.

Appendices 1 and 2 contain numerous examples of actual output from our system. The latter appendix contains questions about the more complex processes of meteorology. Since these questions appear in isolation, we have necessarily set the E state to reflect the appropriate context. Automatic techniques for setting the E vector will be discussed in the CAI section.

Of course, not all questions require the above kind of treatment. Some can be answered directly from the semantic/conceptual network. In fact, the semantic/conceptual network is always consulted first, and only when no responses can be found is the global automaton used. Limited inferences can be obtained directly from the semantic/conceptual network in conjunction with some procedures for processing it. For example, when asked:

Q: What happens to ice when it melts?

it is noted that:

a) Ice is an example of solid water
and b) To melt means by definition to transform solid water into liquid water.

By a simple inferencing procedure which interrelates the SUB relation "is an example of" with XFORM property list we obtain the response:

R: Liquid water.

A slightly more sophisticated example is:

Q: Is it true that fog is a form of precipitation?

Once parsed, a command is set up to access the semantic/conceptual network at the node representing "Precipitation" and a search is made on its value list attached to the property "EX" (examples of). When "Fog" is not encountered, the cross reference list for Fog is searched for a node which references Fog as a value to the property "EX". If such a cross reference exists, that node is processed accordingly. And in this case our system would respond:

R: No, Fog is an example of condensation.

If this cross reference search fails, then a search is made for any object which references it via an "is a kind of" or "is an example of" relation and so on.

Although only "shallow" (with respect to depth of inferencing) inferences are derived from the semantic/conceptual network, it does encode a great deal of information in a sufficiently systematic way that simple inferencing procedures can operate on the network to answer many of the questions that naturally arise in this environment. Again, we stress that our goals are not to build yet another "deep" (with respect to its logical capabilities) question-answering system, but to explore a pragmatic system carefully tuned to the particular environment of a Mixed Initiative type CAI system. As we encode still more information in the network and expand the set of inferencing procedures that operate on it, we expect to discover better ways to structure this network. Seldom, to our knowledge, have there been attempts to encode "large" amounts of information in any kind of conceptual or semantic network structure, although recently there has been some movement in this direction.

A CAI System

The prototype CAI system that we have implemented might be viewed more as a non-directed system rather than as a mixed-initiative system. As such, the student is presented with no required lesson plan and is quite free to "wander at will" through the data base, asking questions at random. Of course such behavior is not expected (and can cause certain problems in the correct setting of the E vector). What is more normal is the type of dialog contained in Appendix 3 which reflects a typical session with the system. In particular, the semantic/conceptual network contains a sequence of nodes representing text frames for each "lesson". The student can request the presentation of any of these frames (currently, these frames are stored as ASCII strings and involve no sentence generation for their presentation). Associated with a frame can be non-displayed information that directly sets the E vector. In addition to selecting a lesson frame, a student can simply request to be told about something, such as:

Q: Tell me something about condensation.

To handle such a request the system determines the conceptual node to access ("Condensation") and searches for the SCH ("Schema") property. The value of this property is a list which specifies the order in which properties are to be accessed in synthesizing responses to such queries. In addition, a pointer is advanced along this list so that when the same question is repeated, or a question is encountered such as:

Q: Tell me something more about condensation

the student will always receive new information (until the knowledge base is exhausted).

The system was originally designed to accept as input a deep structure parse of the student's query produced by a transformational parser currently under development. A key-word parser was developed so that experimentation with the question-answering system could procede independent of the development of the transformational parser. All the examples discussed thus far, and all the output contained in the appendices of this report were parsed by this keyword system. Although successful parses were often obtained, it is, of course, trivial to "fool" this parser.

Conclusion

We feel that we have just begun to realize the potential of representing process type information in these highly specialized automata-like structures. Of special interest is the use of these automata to help in synthesizing complex natural language responses to questions. In other words, we believe that these structures might provide a semantic representation of "causal" structures that is prerequisite to meaningful discourse generation. Also, this representation is obviously useful for the generation of sentences that involve the logical conjunction "because". We are especially excited by having two drastically divergent ways to represent knowledge (i.e., the semantic/conceptual network and the automata) where each modeling structure is especially well suited to handling certain kinds of questions. We were surprised by the relative ease of adding new information to the system and by the amount of knowledge that we finally got encoded into it. With hindsight, we realize how fortuitous the decision was to implement the external and internal conditions for each automaton as LISP predicates instead of restricting ourselves to some Boolean calculus. With the flexibility afforded us by being able to write arbitrarily complex conditions on certain transitions, we could easily add to and modify the automata until they behaved as expected. Of course, the end set of conditions is not necessarily as parsimonious as might be hoped, but then we were not after a theory of meteorology but rather a pragmatic question-answering system that could successfully function in a CAI environment.

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APPENDIX 1

CONTAINER MODEL QUESTIONS

Sample output from questions asked of the system while dealing with the processes of meterology in a closed environment. (Note the first three questions are quanitative while the last is purely qualitative.)

```
Q: (WHAT HAPPENS WHEN THE WATER TEMPERTURE DROPS TO 22
DEGREES)

THE (AIR TEMPERATURE) (DECREASE) FROM 25 TO 22 DEGREES
BECAUSE (WATER TEMPERATURE) (DECREASE). THE (HUMIDITY OF
SATURATION) (DECREASE) FROM 24 TO 20 MM HG BECAUSE (AIR
TEMPERATURE) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN).
THE (RELATIVE HUMIDITY) (INCREASE) FROM 100 TO 120 % BECAUSE
(HUMIDITY OF SATURATION) (DECREASE). THE (RATE OF
EVAPORATION) (DECREASE) FROM 24 TO 20 MM HG BECAUSE (WATER
TEMPERATURE) (DECREASE).

THEN THE (AIR CONDITION) (SUPERSATURATED) BECAUSE (RATE OF
EVAPORATION) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN).
THE (PROCESS) (NET CONDENSATION) BECAUSE (RATE OF
EVAPORATION) (DECREASE) AND (NUCLEI) (HYGROSCOPIC NUCLEI ARE
PRESENT). THE (ABSOLUTE HUMIDITY) (DECREASE) FROM 24 TO 20
MM HG BECAUSE (PROCESS) (NET CONDENSATION). THE (RELATIVE
HUMIDITY) (DECREASE) FROM 120 TO 100 % BECAUSE (ABSOLUTE
HUMIDITY) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE
(RATE OF CONDENSATION) (DECREASE) FROM 24 TO 20 MM HG
BECAUSE (ABSOLUTE HUMIDITY) (DECREASE). THE (AIR CONDITION)
(SATURATED) BECAUSE (RATE OF CONDENSATION) (DECREASE).

THEN THE (PROCESS) (EQUILIBRIUM) BECAUSE (RATE OF
CONDENSATION) (DECREASE).


Q: (WHAT HAPPENS IF THE AIR TEMPERTURE DECREASES TO 20
DEGREES AND THERE ARE NO CONDENSATION NUCLEI)

THE (HUMIDITY OF SATURATION) (DECREASE) FROM 24 TO 17 MM HG
BECAUSE (AIR TEMPERATURE) (DECREASE) AND (GRADIENT OF
CHANGE) (SUDDEN). THE (RELATIVE HUMIDITY) (INCREASE) FROM
100 TO 180 ≤ BECAUSE (HUMIDITY OF SATURATION) (DECREASE).
THE (WATER TEMPERATURE) (DECREASE) FROM 25 TO 20 DEGREES
BECAUSE (AIR TEMPERATURE) (DECREASE). THE (RATE OF
EVAPORATION) (DECREASE) FROM 24 TO 17 MM HG BECAUSE (WATER
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TEMPERATURE) (DECREASE).

THEN THE (AIR CONDITION) (SUPERSATURATED) BECAUSE (RATE OF EVAPORATION) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN).

Q: (WHAT HAPPENS WHEN THE TEMPERTURE INCREASES TO 30)

THE (HUMIDITY OF SATURATION) (INCREASE) FROM 24 TO 32 MM HG BECAUSE (AIR TEMPERATURE) (INCREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (RELATIVE HUMIDITY) (DECREASE) FROM 100 TO 75 % BECAUSE (HUMIDITY OF SATURATION) (INCREASE). THE (WATER TEMPERATURE) (INCREASE) FROM 25 TO 30 DEGREES BECAUSE (AIR TEMPERATURE) (INCREASE). THE (RATE OF EVAPORATION) (INCREASE) FROM 24 TO 32 MM HG BECAUSE (WATER TEMPERATURE) (INCREASE).

THEN THE (AIR CONDITION) (UNSATURATED) BECAUSE (RATE OF EVAPORATION) (INCREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (PROCESS) (NET EVAPORATION) BECAUSE (RATE OF EVAPORATION) (INCREASE). THE (ABSOLUTE HUMIDITY) (INCREASE) FROM 24 TO 32 MM HG BECAUSE (PROCESS) (NET EVAPORATION). THE (RELATIVE HUMIDITY) (INCREASE) FROM 75 TO 100 % BECAUSE (ABSOLUTE HUMIDITY) (INCREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (RATE OF CONDENSATION) (INCREASE) FROM 24 TO 32 DEGREES BECAUSE (ABSOLUTE HUMIDITY) (INCREASE). THE (AIR CONDITION) (SATURATED) BECAUSE (RATE OF CONDENSATION) (INCREASE).

THEN THE (PROCESS) (EQUILIBRIUM) BECAUSE (RATE OF CONDENSATION) (INCREASE).

Q: (SUPPOSE THE PRESSURE DECREASES GRADUALLY).

THE (ABSOLUTE HUMIDITY) (DECREASE) BECAUSE (BAROMETRIC PRESSURE) (DECREASE). THE (RATE OF CONDENSATION) (DECREASE) BECAUSE (ABSOLUTE HUMIDITY) (DECREASE).

THEN THE (PROCESS) (NET EVAPORATION) BECAUSE (RATE OF CONDENSATION) (DECREASE). THE (ABSOLUTE HUMIDITY) (INCREASE) BECAUSE (PROCESS) (NET EVAPORATION). THE (RATE OF CONDENSATION) (INCREASE) BECAUSE (ABSOLUTE HUMIDITY) (INCREASE).

THEN THE (PROCESS) (EQUILIBRIUM) BECAUSE (RATE OF CONDENSATION) (INCREASE).

APPENDIX 2

MODEL METEROLOGY QUESTIONS

Sample output from the system while exploring the processes of meterology in nature.

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Q: (WHAT HAPPENS IF THE AIR TEMPERATURE DROPS TO 22 DEGREES)

THE (WATER TEMPERATURE) (DECREASE) BECAUSE (AIR TEMPERATURE)
(DECREASE).  THE  (RATE OF  EVAPORATION) (DECREASE) BECAUSE
(WATER TEMPERATURE)  (DECREASE) THE (HUMIDITY OF SATURATION)
(DECREASE)   BECAUSE   (AIR   TEMPERATURE)   (DECREASE)  AND
(GRADIENT  OF  CHANGE)  (SUDDEN).   THE  (RELATIVE HUMIDITY)
(INCREASE) BECAUSE (HUMIDITY OF SATURATION) (DECREASE).

THEN THE (AIR CONDITION)  (SUPERSATURATED)  BECAUSE (RATE OF
EVAPORATION)  (DECREASE)  AND (GRADIENT OF CHANGE) (SUDDEN).
THE   (PROCESS)   (NET   CONDENSATION)   BECAUSE   (RATE  OF
EVAPORATION) (DECREASE) AND (NUCLEI) (HYGROSCOPIC NUCLEI ARE
PRESENT).  THE  (NORMAL  WATER  DROPLETS  PRESENT)  BECAUSE
(PROCESS)  (NET  CONDENSATION).   THE  (COALESCENCE PROCESS)
(LARGE AND SMALL WATER DROPLETS FORM) BECAUSE (PROCESS) (NET
CONDENSATION)   AND   (GRADIENT   OF   CHANGE)  (SUDDEN).  THE
(COALESCENCE PROCESS)  (LARGE AND  SMALL WATER DROPLETS FALL
AT DIFFERENT SPEEDS)  BECAUSE (THE LARGER  THE  DROPLET, THE
GREATER THE EFFECT  OF GRAVITY  RELATIVE  TO  THE  EFFECT OF
AERODYNAMIC DRAG).   THE  (COALESCENCE  PROCESS) (COLLISIONS
OCCUR  BETWEEN  LARGE  AND  SMALL  WATER  DROPLETS)  BECAUSE
(COALESCENCE PROCESS)  (LARGE AND SMALL WATER  DROPLETS FALL
AT   DIFFERENT   SPEEDS).   THE   (COALESCENCE   PROCESS)
(COALESCENCE OCCURS)  BECAUSE  (SUFFICIENT  ELECTRICAL FIELD
PRESENT).  THE  (NUMBER  OF  SMALL  PARTICLES) (DIMINISHES)
BECAUSE (COALESCENCE PROCESS) (COALESCENCE OCCURS).

THEN  THE  (COALESCENCE  PROCESS)   (PRECIPITATING  DROPLETS
RESULT)  BECAUSE  (CLOUD  DEPTH) (DEEP).  THE (RAIN) BECAUSE
(COALESCENCE  PROCESS) (PRECIPITATING DROPLETS RESULT).  THE
(COALESCENCE  PROCESS)  (FRACTIONIZATION MAY  OCCUR) BECAUSE
(THE DROPLETS  MAY GROW  BEYOND  7  MM IN DIAMETER, AT WHICH
POINT AERODYNAMIC DRAG MAY PULL THEM APART).  THE (NUMBER OF
SMALL PARTICLES)  (INCREASES)  BECAUSE (COALESCENCE PROCESS)
(FRACTIONIZATION MAY OCCUR).
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Q: (WHAT HAPPENS WHEN THE TEMPERATURE GRADUALLY DROPS TO -10 DEGREES IN A TURBULENT CLOUD)

THE (WATER TEMPERATURE) (DECREASE) BECAUSE (AIR TEMPERATURE) (DECREASE). THE (RATE OF EVAPORATION) (DECREASE) BECAUSE (WATER TEMPERATURE) (DECREASE).

THEN THE (PROCESS) (NET CONDENSATION) BECAUSE (RATE OF EVAPORATION) (DECREASE) AND (NUCLEI) (HYGROSCOPIC NUCLEI ARE PRESENT). THE (SUPER-COOLED WATER DROPLETS PRESENT) BECAUSE (PROCESS) (NET CONDENSATION). THE (HAIL FORMATION PROCESS BEGINS) BECAUSE (SUPER-COOLED WATER DROPLETS PRESENT), (TURBULENCE EXIST) AND (SMALL ICE CRYSTALS PRESENT). THE (COLLISIONS OCCUR) BECAUSE (THE ICE PARTICLES AND WATER DROPLETS ARE MOVING THROUGH THE CLOUD AT VARIOUS VELOCITIES). THE (SUPER-COOLED WATER DROPLETS FREEZE ONTO THE ICE CRYSTALS WHEN THEY COLLIDE WITH THEM) BECAUSE (SUPER-COOLED WATER WILL FREEZE IMMEDIATELY WHEN IT COMES IN CONTACT WITH SOMETHING FOR IT TO FREEZE AROUND). THE (NUMBER OF SUPER-COOLED WATER DROPLETS) (DIMINISHES) BECAUSE (SUPER-COOLED WATER DROPLETS FREEZE ONTO THE ICE CRYSTALS WHEN THEY COLLIDE WITH THEM). THE (PRECIPITATING HAILSTONES RESULT) BECAUSE (TURBULENCE EXIST) AND (CLOUD DEPTH) (DEEP) AND (THESE TWO FACTORS INSURE THAT THE ICE PARTICLES WILL REMAIN IN THE VININITY OF THE SUPER-COOLED WATER DROPLETS LONG ENOUGH TO BECOME RESPECTABLY SIZED HAILSTONES). THE (HAIL) BECAUSE (PRECIPITATING HAILSTONES RESULT).

Q: (WHAT HAPPENS IF THE TEMPERATURE DROPS TO -10 DEGREES SUDDENLY)

THE (HUMIDITY OF SATURATION) (DECREASE) BECAUSE (AIR TEMPERATURE) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (RELATIVE HUMIDITY) (INCREASE) BECAUSE (HUMIDITY OF SATURATION) (DECREASE). THE (WATER TEMPERATURE) (DECREASE) BECAUSE (AIR TEMPERATURE) (DECREASE). THE (RATE OF EVAPORATION) (DECREASE) BECAUSE (WATER TEMPERATURE) (DECREASE).

THEN THE (AIR CONDITION) (SUPERSATURATED) BECAUSE (RATE OF EVAPORATION) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (PROCESS) (NET CONDENSATION) BECAUSE (RATE OF EVAPORATION) (DECREASE) AND (NUCLEI) (HYGROSCOPIC NUCLEI ARE PRESENT). THE (SUPER-COOLED WATER DROPLETS PRESENT) BECAUSE (PROCESS) (NET CONDENSATION). THE (ICE CRYSTAL PROCESS BEGINS) BECAUSE (SUPER-COOLED WATER DROPLETS PRESENT) AND (SMALL ICE CRYSTALS PRESENT). THE (AVERAGE RATE OF CONDENSATION) IS 3.3 MM HG. THE (RATE OF EVAPORATION FROM WATER DROPLETS) IS 4.6 MM HG BECAUSE (THEY ARE IN A LESS STABLE STATE THAN THEIR ACTUAL TEMPERATURE WOULD SEEM TO INDICATE). THE (RATE OF EVAPORATION FROM ICE CRYSTALS) IS 2.1 MM HG THE (ICE PARTICLES GROW AT THE EXPENSE OF THE SUPER-COOLED WATER DROPLETS). THE (PRECIPITATING ICE CRYSTALS RESULT).

APPENDIX 3

SAMPLE OUTPUT DIALOG

(This output sample has been run through a typographic/justifying program in order to make it easier to read. the character strings in this appendix are identical to those generated directly by the Q-A system except that extra spaces have been added in order to achieve justification.)

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Q: BEGIN LESSON ONE

(IN ORDER TO UNDERSTAND PRECIPITATION, WE MUST FIRST
UNDERSTAND ABOUT WATER VAPOR. A SMALL FRACTION (ABOUT 4 ≤)
OF THE ATMOSPHERE IS WATER VAPOR. UNDER NORMAL CONDITIONS,
TINY INCREASES IN THIS SMALL PERCENTAGE CAN RESULT IN
PRECIPITATION. WATER MOLECULES CAN ASSUME THREE DIFFERENT
PHYSICAL STATES: GASEOUS, LIQUID AND SOLID. WATER VAPOR IS
WATER WHICH IS IN THE GASEOUS STATE. WHEN WATER IS IN THE
SOLID STATE, WE CALL IT ICE . WATER AS WE USUALLY THINK OF
IT IS SIMPLY WATER IN THE LIQUID STATE. ALL FORMS OF
PRECIPITATION ARE PRIMARILY COMPOSED OF WATER. IN THE
COURSE OF THIS LESSON WE WILL DISCUSS HOW WATER VAPOR IN THE
ATMOSPHERE IS TRANSFORMED INTO LIQUID OR SOLID STATES AND
FALLS TO THE EARTH).


Q: WHAT IS PRECIPITATION

PRECIPITATION IS (WATER IN LIQUID OR SOLID STATE WHICH FALLS
FROM THE SKY).


Q: WHAT ARE SOME EXAMPLES OF PRECIPITATION

RAIN, SLEET, HAIL AND SNOW


Q: IS FOG A FORM OF PRECIPITATION

NO


Q: WHAT IS FOG
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FOG IS (CLOUDS WHICH ARE FOUND AT VERY LOW ALTITUDES; USUALLY AT LESS THAN A FEW HUNDRED FEET ABOVE GROUND LEVEL).

Q: TELL ME ABOUT WATER VAPOR

WATER VAPOR IS (WATER WHICH IS IN THE GASEOUS OR VAPOR STATE).

Q: BEGIN LESSON TWO

(EVAPORATION IS THE PROCESS BY WHICH LIQUID WATER IS TRANSFORMED INTO WATER VAPOR. IN DAY-TO-DAY LIFE WE SEE MANY EXAMPLES OF EVAPORATION. FOLLOWING A RAIN, FOR INSTANCE, THE PUDDLES ON THE SIDEWALKS SLOWLY VANISH. THIS IS BECAUSE THE LIQUID WATER IN THE PUDDLES EVAPORATES: IT CHANGES INTO WATER VAPOR WHICH DISSOLVES IN THE AIR. CONDENSATION IS THE OPPOSITE PROCESS OF EVAPORATION. CONDENSATION MEANS THAT WATER VAPOR IS TRANSFORMED INTO LIQUID WATER. IF YOU HAVE EVER POURED YOURSELF AN ICE-COLD DRINK ON A WARM DAY, YOU MAY HAVE NOTICED HOW THE OUTSIDE OF THE GLASS BECOMES COATED WITH A THIN FILM OF TINY WATER DROPLETS. THIS IS BECAUSE WATER VAPOR IN THE AIR CONDENSES ON THE COLD SURFACES OF THE GLASS: IT BECOMES THE TINY WATER DROPLETS THAT YOU SEE. EVAPORATION AND CONDENSATION ARE WHAT WE CALL OPPOSING PROCESSES. WHEREVER THERE IS LIQUID WATER, EVAPORATION OCCURS. WHEREVER THERE IS WATER VAPOR, CONDENSATION OCCURS. WHEREVER THERE IS BOTH LIQUID WATER AND WATER VAPOR, THE TWO PROCESSES OCCUR AT THE SAME TIME).

Q: TELL ME ABOUT EVAPORATION

(IF WE TOOK A VERY CLOSE LOOK AT A PUDDLE OF WATER, WE WOULD SEE A COLLECTION OF WATER MOLECULES MOVING IN ALL DIFFERENT DIRECTIONS AT FAIRLY SLOW SPEEDS. NO WATER MOLECULE STAYS IN ONE PLACE FOR VERY LONG, BUT THE AGGREGATE MASS OF WATER MOLECULES WOULD TEND TO STAY CLUMPED FAIRLY TIGHTLY TOGETHER. REMEMBER THAT THE WATER MOLECULES IN THE PUDDLE ARE CONSTANTLY BUMPING INTO EACH OTHER AND ARE THEREFORE CONSTANTLY CHANGING SPEED AND DIRECTION OF MOTION. ALTHOUGH THE AVERAGE SPEED OF THE WATER MOLECULES IS FAIRLY SLOW, SOME OF THEM ARE MOVING FASTER, AND SOME SLOWER, THAN AVERAGE. IF A WATER MOLECULE NEAR THE SURFACE OF THE PUDDLE WAS BUMPED BY OTHER MOLECULES SO THAT IT GAINED THE CORRECT SPEED AND DIRECTION OF MOTION, IT COULD MOVE RIGHT UP THROUGH THE SURFACE OF THE PUDDLE AND BECOME A VAPOR

MOLECULE. THIS IS HOW EVAPORATION OCCURS).

Q: TELL ME MORE ABOUT EVAPORATION

(PUDDLES DRYING UP) AND (FOG BURNING OFF) ARE EXAMPLES OF EVAPORATION

Q: WHAT CAUSES EVAPORATION

(PROCESS) (NET EVAPORATION)MAY BE CAUSED BY (RATE OF EVAPORATION) (INCREASE) OR (RATE OF CONDENSATION) (DECREASE).

Q: TELL ME SOMETHING ABOUT CONDENSATION

(SUPPOSE WE HAVE SOME WATER VAPOR AND SOME LIQUID WATER IN A CONTAINER. ALL THE WATER MOLECULES WHICH MAKE UP THE VAPOR ARE MOVING VERY FAST AND IN ALL DIFFERENT DIRECTIONS. ALSO, THESE VAPOR MOLECULES ARE CONSTANTLY BUMPING INTO EACH OTHER AND INTO THE WALLS OF THE CONTAINER. WHEN THEY BUMP INTO SOMETHING, THEY BOUNCE - RATHER LIKE BILLIARD BALLS. LIKE BILLIARD BUMPING INTO EACH OTHER, TOO, THEY ARE CONSTANTLY CHANGING THEIR DIRECTIONS AND SPEEDS OF TRAVEL. THE WATER MOLECULES IN THE LIQUID WATER MOVE MUCH MORE SLUGGISHLY, AND TEND TO STAY PRETTY MUCH CLUMPED TOGETHER - RATHER LIKE A MASS OF SWARMING BEES. NO SINGLE BEE IN THE SWARM STAYS IN ONE PLACE FOR LONG, BUT THE MASS OF THE SWARM SORT OF STICKS TOGETHER AND SEEMS TO HAVE A FAIRLY CONSTANT VOLUME. THAT'S HOW IT IS WITH THE WATER MOLECULES IN THE LIQUID. SUPPOSE NOW THAT ONE OF THE WATER MOLECULES IN THE VAPOR JUST HAPPENS TO BE HEADED IN THE RIGHT DIRECTION SO THAT IT SMACKS INTO THE SWARM OF LIQUID WATER MOLECULES INSTEAD OF A FAST MOVING VAPOR MOLECULE OR ONE OF THE WALLS OF THE CONTAINER. THE MASS OF SLOW MOVING WATER MOLECULES SOAK UP ITS MOMENTUM AND DISTRIBUTE IT AMONG THEMSELVES. WHAT WAS ONCE A FAST MOVING VAPOR MOLECULE HAS NOW BECOME A SLOW MOVING LIQUID MOLECULE. A LITTLE BIT OF OUR WATER VAPOR HAS CONDENSED INTO LIQUID WATER).

Q: BEGIN LESSON THREE

(AS WE MENTIONED IN THE PREVIOUS LESSON, WHEREVER WATER VAPOR AND LIQUID WATER EXIST TOGETHER, THE PROCESSES OF EVAPORATION AND CONDENSATION OCCUR SIMULTANEOUSLY. WHAT

WILL ULTIMATELY HAPPEN IN SUCH A SITUATION DEPENDS UPON WHICH PROCESS IS OCCURING THE FASTEST. IF THE RATE OF EVAPORATION IS GREATER THAN THE RATE OF CONDENSATION (THAT IS, IF LIQUID WATER IS EVAPORATING FASTER THAN WATER VAPOR IS CONDENSING) THEN THE AMOUNT OF LIQUID WATER WILL DECREASE AND THE AMOUNT OF WATER VAPOR WILL INCREASE. IF THE RATE OF CONDENSATION IS GREATER THAN THE RATE OF EVAPORATION THEN THE AMOUNT OF LIQUID WATER WILL INCREASE AND THE AMOUNT OF WATER VAPOR WILL DECREASE. IN ANY CASE, OF COURSE, THE AMOUNT OF WATER (VAPOR AND LIQUID) WHICH WE HAVE ON HAND WILL REMAIN THE SAME. IF THE RATE OF CONDENSATION IS JUST EQUAL TO THE RATE OF EVAPORATION, THEN WE SAY THAT THE TWO PROCESSES ARE IN A STATE OF EQUILIBRIUM. SINCE WATER IS CONDENSING OUT OF THE VAPOR STATE AS FAST AS IT IS EVAPORATING INTO IT, THE AIR IS NOW HOLDING AS MUCH WATER VAPOR AS IT IS GOING TO UNDER THE PREVAILING CONDITIONS OF TEMPERATURE AND PRESSURE. WE THEREFOR SAY THAT THE AIR IS SATURATED).

Q: WHAT AFFECTS THE RATE OF EVAPORATION

(WATER TEMPERATURE) AND (NUCLEI).

Q: WHAT CAUSES AN INCREASE IN THE RATE OF CONDENSATION

(RATE OF CONDENSATION) (INCREASE)MAY BE CAUSED BY (ABSOLUTE HUMIDITY) (INCREASE).

Q: WHAT HAPPENS IF THE TEMPERATURE INCREASES

THE (HUMIDITY OF SATURATION) (INCREASE) BECAUSE (AIR TEMPERATURE) (INCREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (RELATIVE HUMIDITY) (DECREASE) BECAUSE (HUMIDITY OF SATURATION) (INCREASE). THE (WATER TEMPERATURE) (INCREASE) BECAUSE (AIR TEMPERATURE) (INCREASE). THE (RATE OF EVAPORATION) (INCREASE) BECAUSE (WATER TEMPERATURE) (INCREASE).

THEN THE (AIR CONDITION) (UNSATURATED) BECAUSE (RATE OF EVAPORATION) (INCREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (PROCESS) (NET EVAPORATION) BECAUSE (RATE OF EVAPORATION) (INCREASE). THE (ABSOLUTE HUMIDITY) (INCREASE) BECAUSE (PROCESS) (NET EVAPORATION). THE (RELATIVE HUMIDITY) (INCREASE) BECAUSE (ABSOLUTE HUMIDITY) (INCREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (RATE OF

CONDENSATION) (INCREASE) BECAUSE (ABSOLUTE HUMIDITY) (INCREASE). THE (AIR CONDITION) (SATURATED) BECAUSE (RATE OF CONDENSATION) (INCREASE).

THEN THE (PROCESS) (EQUILIBRIUM) BECAUSE (RATE OF CONDENSATION) (INCREASE).

Q: WHAT HAPPENS IF THE TEMPERATURE INCREASES GRADUALLY

THE (WATER TEMPERATURE) (INCREASE) BECAUSE (AIR TEMPERATURE) (INCREASE). THE (RATE OF EVAPORATION) (INCREASE) BECAUSE (WATER TEMPERATURE) (INCREASE).

THEN THE (PROCESS) (NET EVAPORATION) BECAUSE (RATE OF EVAPORATION) (INCREASE). THE (ABSOLUTE HUMIDITY) (INCREASE) BECAUSE (PROCESS) (NET EVAPORATION). THE (RATE OF CONDENSATION) (INCREASE) BECAUSE (ABSOLUTE HUMIDITY) (INCREASE).

THEN THE (PROCESS) (EQUILIBRIUM) BECAUSE (RATE OF CONDENSATION) (INCREASE).

Q: BEGIN LESSON FOUR

(BEFORE PROCEEDING INTO A DETAILED STUDY OF THE PHYSICS OF METEOROLOGY, WE WILL HAVE TO DEVOTE SOME ATTENTION TO MEASURING OR QUANTIFYING THE CONCEPTS INTRODUCED IN THE PREVIOUS LESSONS. TO BEGIN WITH, WE WILL DEFINE THE TERM ABSOLUTE HUMIDITY TO MEAN THE AMOUNT OF WATER VAPOR IN THE AIR. SINCE WATER VAPOR IS A GAS, ABSOLUTE HUMIDITY IS MEASURED AS A PRESSURE. ANY UNITS OF PRESSURE ARE SATISFACTORY (ATMOSPHERES, MILLIBARS, INCHES OF MERCURY) BUT, SINCE WE ARE ADVOCATES OF THE METRIC SYSTEM, WE WILL MEASURE PRESSURE THROUGHOUT THIS DISCUSSION IN MILLIMETRES OF MERCURY (ABBREVIATED MM.-HG.) WHEN WE SAY THAT THE AIR IS UNSATURATED (OR NOT SATURATED) WITH WATER VAPOR, WE MEAN THAT THE RATE OF EVAPORATION OF LIQUID WATER INTO THE AIR IS GREATER THAN THE RATE OF CONDENSATION OF WATER VAPOR OUT OF THE AIR. WHEN WE SAY THAT THE AIR IS SUPER-SATURATED WITH WATER VAPOR, WE MEAN THAT THE ABSOLUTE HUMIDITY OR RATE OF CONDENSATION IS GREATER THAN THE RATE OF EVAPORATION. WHEN THESE TWO RATES ARE JUST EQUAL, WE SAY THAT THE AIR IS SATURATED WITH WATER VAPOR. HUMIDITY OF SATURATION WE WILL DEFINE AS THE ABSOLUTE HUMIDITY AT WHICH THE RATE OF CONDENSATION SHOULD EQUAL THE RATE OF EVAPORATION. SINCE THE RATE OF EVAPORATION VARIES AS A FUNCTION OF THE

TEMPERATURE, THE HUMIDITY OF SATURATION DOES ALSO. THE TERM RELATIVE HUMIDITY IS SIMPLY DEFINED AS THE ABSOLUTE HUMIDITY DIVIDED BY THE HUMIDITY OF SATURATION, THE ANSWER BEING EXPRESSED AS A PERCENTAGE BY MULTIPLYING THE QUOTIENT BY ONE HUNDRED. AS WE CAN EASILY SEE FROM ITS DEFINITION, THE RELATIVE HUMIDITY SHOULD IDEALLY BE EQUAL TO 100 ≤ WHENEVER THE AIR IS SATURATED. LATER ON, HOWEVER, WE WILL DEAL WITH CASES IN WHICH THE AIR BECOMES SATURATED AT RELATIVE HUMIDITIES LESS THAN 100 ≤).

Q: WHAT THINGS CAN CAUSE AN INCREASE IN THE RELATIVE HUMIDITY

(RELATIVE HUMIDITY) (INCREASE)MAY BE CAUSED BY (HUMIDITY OF SATURATION) (DECREASE) OR (ABSOLUTE HUMIDITY) (INCREASE) AND (GRADIENT OF CHANGE) (SUDDEN).

Q: WHAT AFFECTS THE RATE OF CONDENSATION

(ABSOLUTE HUMIDITY).

Q: BEGIN LESSON FIVE

(SUPPOSE WE PLACE A SMALL AMOUNT OF WATER ALONG WITH A QUANTITY OF PERFECTLY DRY AIR INTO A LARGE CONTAINER WHICH WE SEAL AND KEEP AT A CONSTANT TEMPERATURE. THE WATER LEVEL INSIDE THE CONTAINER WILL DROP AS THE WATER BEGINS TO EVAPORATE AND, AS MORE AND MORE OF THE WATER TURNS INTO WATER VAPOR, THE ABSOLUTE HUMIDITY WILL INCREASE. SINCE THE RATE OF EVAPORATION IN THIS INSTANCE DEPENDS SOLELY ON THE TEMPERATURE OF THE WATER, WHICH IS BEING KEPT CONSTANT, THE RATE OF EVAPORATION WILL ALWAYS REMAIN AT ITS INITIAL VALUE. THE RATE OF CONDENSATION, HOWEVER, WILL INCREASE AS THE ABSOLUTE HUMIDITY INCREASES: THE MORE WATER MOLECULES THERE ARE IN THE AIR, THE MORE OF THEM THERE WILL BE BUMPING INTO THE SURFACE OF THE WATER (THAT IS, CONDENSING) . AFTER A PERIOD OF TIME, THE RATE OF CONDENSATION WILL INCREASE UNTIL IT EXACTLY EQUALS THE RATE OF EVAPORATION AND THE WATER LEVEL INSIDE THE CONTAINER WILL CEASE TO FALL. AT THIS POINT, THE AIR INSIDE THE CONTAINER WILL BE SATURATED AND THE RELATIVE HUMIDITY INSIDE THE CONTAINER WILL BE EXACTLY 100 ≤. SINCE THE WATER LEVEL HAS STOPPED FALLING, WE WOULD NATURALLY SAY THAT THE WATER HAS STOPPED EVAPORATING. FROM A MORE PRECISE POINT OF VIEW, HOWEVER, THE WATER IS STILL EVAPORATING; IT IS SIMPLY THAT WATER VAPOR IS NOW CONDENSING

BACK INTO LIQUID WATER JUST AS QUICKLY, AND, THEREFORE, THE TOTAL AMOUNT OF LIQUID WATER REMAINS THE SAME. IN ORDER TO AVOID AMBIGUITY, WE WILL CALL THE TYPE OF EVAPORATION WHICH MEANS A LOWERING OF THE WATER LEVEL : NET EVAPORATION. SIMILARLY, WHEN THE AMOUNT OF LIQUID WATER INCREASES BECAUSE THE RATE OF CONDENSATION IS GREATER THAN THE RATE OF EVAPORATION, WE WILL SAY THAT A PROCESS OF NET CONDENSATION IS OCCURRING).

Q: TELL ME MORE ABOUT CONDENSATION

(CLOUDS FORMING), (DEW FORMING ON THE GRASS) AND (WINDOWS FOGGING UP) ARE EXAMPLES OF CONDENSATION

Q: WHAT ARE CONDENSATION NUCLEI

CONDENSATION NUCLEI ARE (PARTICLES SO SMALL THAT THEY CAN EASILY BECOME SUSPENDED IN THE AIR. THEY PROVIDE A PLACE OR SURFACE UPON WHICH THE PROCESS OF CONDENSATION CAN BEGIN. THE MOST COMMON TYPE OF CONDENSATION NUCLEI ARE DUST PARTICLES).

Q: TELL ME ABOUT HYGROSCOPIC NUCLEI

HYGROSCOPIC NUCLEI ARE SMALL PARTICLES (USUALLY ONLY A FEW MICRONS IN DIAMETER) WHICH CAN BECOME AIRBORN AND WHICH ATTRACT WATER VAPOR. THE MOST USUAL TYPE OF HYGROSCOPIC NUCLEI ARE SMALL SALT PARTICLES BLOWN UP FROM THE OCEANS.

Q: WHAT HAPPENS IF THE TEMPERATURE DECREASES SUDDENLY AND NO SURFACES OR NUCLEI ARE AVAILABLE

THE (HUMIDITY OF SATURATION) (DECREASE) BECAUSE (AIR TEMPERATURE) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (RELATIVE HUMIDITY) (INCREASE) BECAUSE (HUMIDITY OF SATURATION) (DECREASE). THE (WATER TEMPERATURE) (DECREASE) BECAUSE (AIR TEMPERATURE) (DECREASE). THE (RATE OF EVAPORATION) (DECREASE) BECAUSE (WATER TEMPERATURE) (DECREASE).

THEN THE (AIR CONDITION) (SUPERSATURATED) BECAUSE (RATE OF EVAPORATION) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN).

Q: WHAT HAPPENS IF THE WATER TEMPERATURE INCREASES

THE (AIR TEMPERATURE) (INCREASE) BECAUSE (WATER TEMPERATURE) (INCREASE). THE (HUMIDITY OF SATURATION) (INCREASE) BECAUSE (AIR TEMPERATURE) (INCREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (RELATIVE HUMIDITY) (DECREASE) BECAUSE (HUMIDITY OF SATURATION) (INCREASE). THE (RATE OF EVAPORATION) (INCREASE) BECAUSE (WATER TEMPERATURE) (INCREASE).

THEN THE (AIR CONDITION) (UNSATURATED) BECAUSE (RATE OF EVAPORATION) (INCREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (PROCESS) (NET EVAPORATION) BECAUSE (RATE OF EVAPORATION) (INCREASE). THE (ABSOLUTE HUMIDITY) (INCREASE) BECAUSE (PROCESS) (NET EVAPORATION). THE (RELATIVE HUMIDITY) (INCREASE) BECAUSE (ABSOLUTE HUMIDITY) (INCREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (RATE OF CONDENSATION) (INCREASE) BECAUSE (ABSOLUTE HUMIDITY) (INCREASE). THE (AIR CONDITION) (SATURATED) BECAUSE (RATE OF CONDENSATION) (INCREASE).

THEN THE (PROCESS) (EQUILIBRIUM) BECAUSE (RATE OF CONDENSATION) (INCREASE).

Q: BEGIN LESSON SIX

(ALTHOUGH METEOROLOGISTS HAVE CLASSIFIED MANY DIFFERENT TYPES OF CLOUDS AND ASSIGNED NAMES TO EACH, ALL CLOUDS CONSIST MAINLY OF ONE OR MORE OF THREE TYPES OF WATER PARTICLES. MOST CLOUDS ARE COMPOSED OF NORMAL WATER DROPLETS WHICH ARE TINY ENOUGH TO REMAIN SUSPENDED IN THE AIR. THESE DROPLETS FORM WHEN NET CONDENSATION OCCURS ON TINY DUST OR SALT PARTICLES WHICH ARE CALLED CONDENSATION NUCLEI. CLOUD DROPLETS WHICH FORM THIS WAY ARE PRACTICALLY FREE OF IMPURITIES. ALTHOUGH WATER ORDINARLIY FREEZES WHEN THE TEMPERATURE DROPS BELOW ZERO DEGREES CENTIGRADE, VERY PURE WATER (SUCH AS IS FOUND IN CLOUD DROPLETS) CAN REMAIN IN THE LIQUID STATE UNTIL THE TEMPERATURE DROPS TO ALMOST FORTY DEGREES BELOW ZERO. LIQUID WATER FOUND AT TEMPERATURES BELOW ZERO CENTIGRADE IS SAID TO BE SUPERCOOLED. SUPERCOOLED WATER DROPLETS (THE SECOND OF OUR THREE TYPES OF CLOUD WATER PARTICLES) WILL REMAIN LIQUID UNTIL THE TEMPERATURE DROPS BELOW THE CRITICAL LEVEL OR UNTIL THEY ENCOUNTER FREEZING NUCLEI. ALL FREEZING NUCLEI HAVE CRYSTALLINE STRUCTURES. THESE TINY CRYSTALS PROVIDE A SEED FOR THE LIQUID WATER TO CRYSTALLIZE (FREEZE) AROUND. THE MOST EFFICIENT NATURALLY OCCURRING FREEZING NUCLEI ARE

VERY MINUTE ICE CRYSTALS. THE CLOUD DROPLETS THAT FREEZE IN THIS WAY BECOME THE TINY ICE CRYSTALS WHICH ARE, OF COURSE, OUR THIRD TYPE OF CLOUD PARTICLE).

Q: TELL ME MORE ABOUT CLOUDS

(CLOUDS ARE MASSES OF TINY WATER DROPLETS OR ICE CRYSTALS WHICH HANG SUSPENDED IN THE AIR. GENERALLY A CLOUD WILL CONTAIN ONE HUNDRED MILLION OR SO PARTICLES EACH OF WHICH IS BETWEEN ABOUT TWO AND TWO HUNDRED MICRONS IN DIAMETER).

Q: WHAT ARE SOME TYPES OF CLOUDS

CUMULUS, CIRRUS, NIMBUS, AND CUMULO-NIMBUS

Q: WHAT ARE SOME EXAMPLES OF FREEZING NUCLEI

SALT, ICE CRYSTALS AND SILVER IODIDE

Q: BEGIN LESSON SEVEN

(CLOUD PARTICLES ARE TINY ENOUGH TO REMAIN SUSPENDED IN THE ATMOSPHERE. WHEN CLOUD PARTICLES BECOME TOO LARGE TO REMAIN IN SUSPENSION, THEY BECOME PRECIPITATION AND FALL TO THE EARTH. THERE ARE TWO KNOWN PROCESSES BY WHICH PRECIPITATING PARTICLES OTHER THAN HAIL MAY BE GROWN INSIDE OF CLOUDS. THE FIRST OF THESE IS CALLED THE COALESCENCE PROCESS. THIS PROCESS OCCURS IN CLOUDS COMPOSED OF WATER DROPLETS OF VARYING SIZES. THE LARGER DROPLETS FALL TO THE BOTTOM OF THE CLOUD MORE QUICKLY THAN THE SMALLER ONES AND COLLIDE AND MERGE WITH THEM. IF THE CLOUD IS DEEP ENOUGH, DROPLETS CAN GROW IN THIS MANNER TO BECOME QUITE SUBSTANTIAL RAINDROPS. THE SECOND PROCESS IS CALLED THE ICE CRYSTAL PROCESS. THIS PROCESS OCCURS IN CLOUDS COMPOSED OF SUPERCOOLED WATER DROPLETS AND SMALL ICE CRYSTALS. SINCE SUPERCOOLED WATER EVAPORATES MORE QUICKLY THAN DO THE ICE CRYSTALS, THE ICE CRYSTALS GROW WHILE THE DROPLETS SHRINK. IN THIS MANNER, PRECIPITATING ICE CRYSTALS (SNOW) ARE FORMED IN CLOUDS. IF THERE IS A STRONG UPDRAFT OR TURBULENCE INSIDE THE CLOUD, THESE LARGER ICE CRYSTALS MAY REMAIN NEAR THE SUPERCOOLED WATER DROPLETS LONGER THAN THEY OTHERWISE WOULD. WHEN COLLISIONS OCCUR BETWEEN THESE ICE CRYSTALS AND THE WATER DROPLETS, THE SUPERCOOLED LIQUID WATER FREEZES ONTO THE CRYSTALS ALMOST INSTANTANEOUSLY. THE ICE PARTICLES BECOME

LARGER AND LARGER. IF THE PROCESS CONTINUES FOR LONG ENOUGH, THEY CAN BECOME LARGE HAILSTONES WHICH WILL EVENTUALLY FALL OUT OF THE CLOUD).

Q: WHAT HAPPENS IF THE AIR TEMPERATURE DECREASES

THE (HUMIDITY OF SATURATION) (DECREASE) BECAUSE (AIR TEMPERATURE) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (RELATIVE HUMIDITY) (INCREASE) BECAUSE (HUMIDITY OF SATURATION) (DECREASE). THE (WATER TEMPERATURE) (DECREASE) BECAUSE (AIR TEMPERATURE) (DECREASE). THE (RATE OF EVAPORATION) (DECREASE) BECAUSE (WATER TEMPERATURE) (DECREASE).

THEN THE (AIR CONDITION) (SUPERSATURATED) BECAUSE (RATE OF EVAPORATION) (DECREASE) AND (GRADIENT OF CHANGE) (SUDDEN). THE (PROCESS) (NET CONDENSATION) BECAUSE (RATE OF EVAPORATION) (DECREASE) AND (NUCLEI ARE PRESENT). THE (NORMAL WATER DROPLETS PRESENT) BECAUSE (PROCESS) (NET CONDENSATION). THE (COALESCENCE PROCESS) (LARGE AND SMALL WATER DROPLETS FORM) BECAUSE (PROCESS) (NET CONDENSATION) AND (GRADIENT OF CHANGE) (SUDDEN). THE (COALESCENCE PROCESS) (LARGE AND SMALL WATER DROPLETS FALL AT DIFFERENT SPEEDS) BECAUSE (THE LARGER THE DROPLET, THE GREATER THE EFFECT OF GRAVITY RELATIVE TO THE EFFECT OF AERODYNAMIC DRAG). THE (COALESCENCE PROCESS) (COLLISIONS OCCUR BETWEEN LARGE AND SMALL WATER DROPLETS) BECAUSE (COALESCENCE PROCESS) (LARGE AND SMALL WATER DROPLETS FALL AT DIFFERENT SPEEDS). THE (COALESCENCE PROCESS) (COALESCENCE OCCURS) BECAUSE (SUFFICIENT ELECTRICAL FIELD PRESENT). THE (NUMBER OF SMALL PARTICLES) (DIMINISHES) BECAUSE (COALESCENCE PROCESS) (COALESCENCE OCCURS).

THEN THE (COALESCENCE PROCESS) (PRECIPITATING DROPLETS RESULT) BECAUSE (CLOUD DEPTH) (DEEP). THE (RAIN) BECAUSE (COALESCENCE PROCESS) (PRECIPITATING DROPLETS RESULT). THE (COALESCENCE PROCESS) (FRACTIONIZATION MAY OCCUR) BECAUSE (THE DROPLETS MAY GROW BEYOND 7 MM IN DIAMETER, AT WHICH POINT AERODYNAMIC DRAG MAY PULL THEM APART). THE (NUMBER OF SMALL PARTICLES) (INCREASES) BECAUSE (COALESCENCE PROCESS) (FRACTIONIZATION MAY OCCUR). THE (COALESCENCE PROCESS) (COALESCENCE OCCURS). THE (NUMBER OF SMALL PARTICLES) (DIMINISHES) BECAUSE (COALESCENCE PROCESS) (COALESCENCE OCCURS).

THEN THE (COALESCENCE PROCESS) (PRECIPITATING DROPLETS RESULT) BECAUSE (CLOUD DEPTH) (DEEP). THE (RAIN) BECAUSE

(COALESCENCE PROCESS) (PRECIPITATING DROPLETS RESULT).

Q: ARE TYPHOON THUNDERSTORM AND DRIZZLE EXAMPLES OF STORM

THUNDERSTORM AND TYPHOON ARE BUT DRIZZLE IS NOT.

APPENDIX 4

DESCRIPTION OF THE AUTOMATON MODEL

This is a description of the automaton model for meterological processes. The automatom is made up of a collection of sub-automata. The state of the global automaton is defined by the collection of the states of the sub-automata. The interaction between the sub-automata determine the transition of the global automaton.

These are the sub-automata currently incorporated in the system. Following the description of each automaton is a list of its states and the possible transitions which may occur between these states. The computation and default value are given for those sub-automata which have quanitative parts associated with them.

(Notational notes: Interpret square brackets ([]) to mean "state of"; thus, read [IA] as "the state of the Humidity of Saturation". Interpret opposed double angle brackets (<<>>) to mean "the value of"; thus read <<A.T.>> as "the value of the Air Temperature", meaning the numerical value of this variable rather than the state of the automaton which represents changes in this value. Terms or disjuncts of transition conditions which are flagged with an "*" are to be suppressed from output generated by the model in order to eliminate redundant or pedagogically irrelevant process requirements from reaching the student. Due to typographic limitations, take "#" to mean "not equal to", "V" to mean "inclusive or" and "/" to mean "logical 'and'".)

PHYSICAL PARAMETRIC AUTOMATA

Parametric automata are those which describe values of physical parameters, such as Air Temperature, Barometric Pressure, etc.

AIR TEMPERATURE - Ambient air temperature obtained at the site of the described processes.

[A.T.] (AIR TEMPERATURE)

A = "DECREASES"
B = "STABLE"
C = "INCREASES"

B=>A (SPEC)* V (([W.T.]=A)/([S]=T))
B=>C (SPEC)* V (([W.T.]=C)/([S]=T))

COMPUTATIONAL NOTE:
UNITS = DEGREES CENTIGRADE (C)
DEFAULT VALUE = 25 C

WATER TEMPERATURE - Average temperature of masses of water participating in described processes. In the case of meteorological processes, the participating masses of water are assumed to be water droplets which are at essentially the same temperature as the air.

[W.T.] (WATER TEMPERATURE)
A = "DECREASES"
B = "STABLE"
C = "INCREASES"

B=>A (SPEC)* V (([A.T.]=A)/([S]=T))
B=>C (SPEC)* V (([A.T.]=A)/([S]=T))

COMPUTATIONAL NOTE:
UNITS = DEGREES CENTIGRADE
DEFAULT VALUE ([S]=T) = 25 C
([S]=F) = 18 C

BAROMETRIC PRESSURE - Average barometric pressure at the site of the described processes.

[B.P.] (BAROMETRIC PRESSURE)
A = "DECREASES"
B = "STABLE"
C = "INCREASES"

B=>A (SPEC)*
B=>C (SPEC)*

COMPUTATIONAL NOTE:
UNITS = MILLIMETRES OF MERCURY (MM HG)
DEFAULT VALUE = 760 MM HG

CENTRAL AUTOMATA

Central automata are those which are employed in the solution of container problems and in the preliminary considerations of the formation of airborn particles (clouds).

HUMIDITY OF SATURATION - The absolute humidity at which the rate of condensation should just equal the rate of evaporation, assuming the air temperature to be equal to the water temperature and the absence of hygroscopic nuclei or other mechanisms which would interfere with the rate of evaporation. This value is a dependent variable of the air temperature.

```
[IA]  (HUMIDITY OF SATURATION)
  A = "DECREASES"
  B = "STABLE"
  C = "INCREASES"

  B=>A  ([A.T.]=A)
  B=>C  ([A.T.]=C)

COMPUTATIONAL NOTE:
<<IA>> = TABLE(<<A.T.>>)
```

RATE OF EVAPORATION - The rate at which liquid water is being converted into water vapor, measured at the boundary between the liquid water and the air, expressed as a pressure. This quantity is essentially the same as the vapor pressure of water measured over the same boundary.

```
[IB]  (RATE OF EVAPORATION)
  A = "DECREASES"
  B = "STABLE"
  C = "INCREASES"

  B=>A  ([W.T.]=A) V ([N] X=>B (X#B))
  B=>C  ([W.T.]=C) V ([N] B=>X (X#B))

COMPUTATIONAL NOTE:
<<O>>=1 IF ([N]=B)
<<Q>>=0 IF ([N]#B)
<<IB>> = TABLE(<<W.T.>>)-<<O>>*1.5*TABLE(<<W.T.>>)
```

ABSOLUTE HUMIDITY - The partial pressure of water vapor in the atmosphere at the site of the described process.

```
[IIA]  (ABSOLUTE HUMIDITY)
  A = "DECREASES"
  B = "STABLE"
  C = "INCREASES"

  B=>A  ([B.P.]=A) V (([III]=C)/([P]=C)*)
  B=>C  ([B.P.]=C) V (([III]=A)/([P]=C)*)
```

```
COMPUTATIONAL NOTE:
<<IIA>> = <<IB>> IF [IIA] TRIGGERED BY [III]
<<IIA>>' = (<<B.P.>>'/<<B.P.>>)*<<IIA>>
                IF [IIA] TRIGGERED BY [B.P.]
                     (' MEANS NEW VALUE)
```

RATE OF CONDENSATION - The rate at which water vapor is returning to the liquid state measured as a pressure upon the air-water boundary. The value is essentially equal to the partial pressure of water vapor in the air.

```
[IIB]  (RATE OF CONDENSATION)
  A = "DECREASES"
  B = "STABLE"
  C = "INCREASES"

  B=>A  ([IIA]=A)
  B=>C  ([IIA]=C)
```

```
COMPUTATIONAL NOTE:
<<IIB>> = <<IIA>>
```

PROCESS - This graph describes the imbalance between the rates of evaporation and condensation as net evaporation, net condensation or equilibrium.

```
[III]  (PROCESS)
  A = "NET EVAPORATION"
  B = "EQUILIBRIUM"
  C = "NET CONDENSATION"

  B=>A  ([IB]=C) V ([IIB]=A)
  B=>C  ([IB]=A) V ([IIB]=C)
  A=>B  ([IIB]=C)
```

C=>B ([IIB]=A)

RELATIVE HUMIDITY - The absolute humidity divided by the humidity of saturation, the quotient being expressed as a percentage.

[IV] (RELATIVE HUMIDITY)
A = "DECREASES"
B = "STABLE"
C = "INCREASES"

B=>A ([IA]=C) V ([IIA]=A)
B=>C ([IA]=A) V ([IIA]=C)

COMPUTATIONAL NOTE:
<<IV>> = (<<IIA>>/<<IA>>)*100

AIR BECOMES - This graph describes the air as being either saturated, unsaturated or super-saturated, depending on how the rates of condensation and evaporation compare.

[V] (AIR BECOMES)
A = "UNSATURATED"
B = "SATURATED"
C = "SUPER-SATURATED"

B=>A (([IB]=C) V ([IIB]=A))/([G]=B)
B=>C (([IB]=A) V ([IIB]=C))/([G]=B)
A=>B ([III]=A)*/([IIB]=C)
C=>B ([III]=C)*/([IIB]=A)

PROCESS CHAIN AUTOMATA

ICPROG - This graph describes the various conceptual stages of the ice crystal process. Various states in this process chain are individually devoted to examinations of the physical forces which drive the Ice Crystal Process and of certain requirements which must be satisfied in order for this process to occur.

[ICPROG] (PROGRESS OF ICE CRYSTAL PROCESS)
A = "PROCESS DOES NOT OCCUR"

```
  B = "THE ICE CRYSTAL PROCESS BEGINS"
  C = "AVERAGE RATE OF CONDENSATION = <<ARCD>>"
  D = "RATE OF EVAPORATION FROM WATER DROPLETS = <<REWD>>"
  E = "RATE OF EVAPORATION FROM ICE CRYSTALS = <<REIC>>"
  F = "ICE PARTICLES GROW AT THE EXPENSE OF THE SUPER-COOLED
       WATER DROPLETS"
  G = "PRECIPITATING ICE CRYSTALS RESULT"

  A=>B  ([SCWD]=T)/([IC]=T)
  B=>C    (FORCED)*
  C=>D  (FORCED)*:  "THEY ARE IN A LESS STABLE STATE THAN
                THEIR ACTUAL TEMPERATURE WOULD SEEM TO INDICATE."
  D=>E  (FORCED)*
  E=>F  ([SSC]=A)/([SIC]=C)
  F=>G  ([D]=F)*: "IF THE PROCESS CONTINUES FOR LONG ENOUGH,
        THE PARTICLES WILL GROW LARGE ENOUGH TO FALL FROM THE
        CLOUD."

COMPUTATIONAL NOTE:
<<REIC>> = TABLE(<<A.T.>>)
<<REWD>> = TABLE( 0 )
<<ARCD>> = (<<REIC>>+<<REWD>>)/2
```

HFPROG - This graph describes the various conceptual stages of the Hail Formation Process in the above manner.

```
[HFPROG]  (PROGRESS OF HAIL FORMATION PROCESS)
  A = "PROCESS DOES NOT OCCUR"
  B = "THE HAIL FORMATION PROCESS BEGINS"
  C = "COLLISIONS OCCUR"
  D = "SUPER-COOLED WATER DROPLETS FREEZE ONTO THE ICE
       CRYSTALS WHEN THEY COLLIDE WITH THEM"
  E = "PRECIPITATING HAILSTONES RESULT"

  A=>B  ([SCWD]=T)/([IC]=T)/([T]=T)*/([C]=D)
  B=>C  (FORCED)*:  "THE ICE PARTICLES AND WATER DROPLETS
             ARE MOVING THROUGH THE CLOUD AT RANDOM VELOCITIES."
  C=>D  (FORCED)*:  "SUPER-COOLED WATER WILL FREEZE
         IMMEDIATELY WHEN IT COMES IN CONTACT WITH SOMETHING
         FOR IT TO FREEZE AROUND."
  D=>E  ([T]=T)/([C]=D):  "THESE TWO FACTORS INSURE THAT
        THE ICE PARTICLES WILL REMAIN IN THE VICINITY OF THE
        SUPER-COOLED WATER DROPLETS LONG ENOUGH TO BECOME
        RESPECTABLY SIZED HAILSTONES."
```

FRPROG - This graph details the "cloud freezing" process which occurs when clouds of super-cooled water droplets encounter freezing nuclei.

[FRPROG] (PROGRESS OF THE CLOUD FREEZING PROCESS)
A = "PROCESS DOES NOT OCCUR"
B = "A CLOUD CAN BEGIN TO FREEZE"
C = "COLLISIONS OCCUR"
D = "WHEN DROPLETS COLLIDE WITH FREEZING NUCLEI, THEY BECOME SMALL ICE CRYSTALS"

A=>B ([SCWD]=T)/([FN]=T)/([IC]=F)*
B=>C (FORCED)*: "ALL THE PARTICLES IN THE CLOUD ARE MOVING WITH RANDOM VELOCITIES."
C=>D (FORCED)*: "THE CRYSTALLINE FREEZING NUCLEI CAN PROVIDE SOMETHING FOR THE SUPER-COOLED WATER TO CRYSTALLIZE (FREEZE) AROUND."

COPROG - This graph describes the various conceptual stages of the coalescence process in a manner identical to the foregoing.

[COPROG] (PROGRESS OF COALESCENCE PROCESS)
A = "PROCESS DOES NOT OCCUR"
B = "LARGE AND SMALL WATER DROPLETS FORM"
C = "LARGE AND SMALL WATER DROPLETS FALL AT DIFFERENT SPEEDS"
D = "COLLISIONS OCCUR BETWEEN DIFFERENT SIZE WATER DROPLETS"
E = "COALESCENCE OCCURS"
F = "PRECIPITATING DROPLETS RESULT"
G = "FRACTIONATION MAY OCCUR"

A=>B ([NWD]=T)*/([G]=B)/([E]=T)*/([C]=D)*
B=>C (FORCED)*: "THE LARGER THE DROPLET, THE GREATER THE EFFECT OF GRAVITY RELATIVE TO THE EFFECT OF AERODYNAMIC DRAG."
C=>D ([COPROG]=C)
D=>E ([E]=T)
E=>F ([C]=D)
F=>G (FORCED ON FIRST ENCOUNTER OF STATE "F")*: "THE DROPLETS MAY GROW BEYOND 7 MM. IN DIAMETER, AT WHICH POINT AERODYNAMIC DRAG MAY PULL THEM APART."

AUTOMATON FOR PRECIPITATION FORMS

PRECIPIFORM - This graph describes changes in the attributes or types of forms of precipitation which occur due to other changes in the model. The transition structure for this graph describes, for instance, how it is possible for snow to melt before reaching the ground.

```
[PRECIPIFORM]  (FORM OF PRECIPITATION)
  A = "RAIN"
  B = "SNOW"
  C = "HAIL"
  D = "SLEET"
  E = "NO PRECIPITATION"

  E=>A  ([COPROG]=F)
  E=>B  ([ICPROG]=G)
  E=>C  ([HFPROG]=E)
  A=>E  ([ATLA]=H)
  A=>D  ([ATLA]=C)
  B=>A  ([ATLA]=W)
  C=>A  ([ATLA]=W)
```

SUBSIDIARY PROCESS AUTOMATA

Subsidairy automata form small sub-models which are triggered and controlled by the main process chains. Their purpose is to help in explaining the individual discrete processes which compose those complex processes (e.g., Ice Crystal process).

NET - This graph delineates net processes which occur during and which embody the Ice Crystal process.

```
[NET]  (PROCESS)
  A = "NET EVAPORATION"
  B = "EQUILIBRIUM"
  C = "NET CONDENSATION"

  B=>A  (<<REIC>> > <<ARCD>>) V (<<REWD>> > <<ARCD>>)
  B=>C  (<<REIC>> < <<ARCD>>) V (<<REWD>> < <<ARCD>>)
```

SSC - Describes the average size of super-cooled water droplets in an attempt to flesh out the descriptions generated by the ICPROG process chain.

[SSC] (SIZE OF SUPER-COOLED WATER DROPLETS)
A = "DIMINISHES"
B = "REMAINS CONSTANT"
C = "INCREASES"

B=>A ([ICPROG]=D)*/([NET]=A)
B=>C ([ICPROG]=D)*/([NET]=C)

SIC - Augments the ICPROG and HFPROG process chains by describing the average size of ice crystals present in the clouds in which these processes occur.

[SIC] (SIZE OF ICE CRYSTALS)
A = "DIMINISHES"
B = "REMAINS CONSTANT"
C = "INCREASES"

B=>A ([ICPROG]=E)*/([NET]=A)
B=>C ([ICPROG]=E)*/([NET]=C) V ([HFPROG]=D)

NSC - Developed for the benefit of the HFPROG process chain, this graph describes the number of super-cooled water droplets present in a hail-forming cloud. By means of this graph, changes in the composition of the cloud can be broadly indicated.

[NSC] (NUMBER OF SUPER-COOLED WATER DROPLETS)
A = "DIMINISHES"
B = "REMAINS CONSTANT"
C = "INCREASES"

B=>A ([HFPROG]=D)

NIC - Describes changes in the amounts of ice crystals present in the cloud.

[NIC] (NUMBER OF ICE CRYSTALS)
A = "DIMINISHES"
B = "REMAINS CONSTANT"
C = "INCREASES"

B=>C ([FRPROG]=D)

SPI - Acts similarly to describe the number of water droplets present in the cloud which are below the average size (according to the statistical distribution obtained before the process begins).

[SPI] (NUMBER OF SMALL DROPLETS)
A = "DIMINISHES"
B = "REMAINS CONSTANT"
C = "INCREASES"

B=>A ([COPROG]=E)
B=>C ([COPROG]=G)

LPI - Describes similarly droplets above average size.

[LPI] (NUMBER OF LARGE DROPLETS]
A = "DIMINISHES"
B = "REMAINS CONSTANT"
C = "INCREASES"

B=>A ([COPROG]=G)
B=>C ([COPROG]=E)

LPII - DESCRIBES CHANGES IN THE AVERAGE SIZE OF LARGE CLOUD PARTICLES AS COALESCENCE OCCURS.

[LPII] (SIZE OF LARGE DROPLETS)
A = "DIMINISHES"
B = "REMAINS CONSTANT"
C = "INCREASES"

B=>A ([COPROG]=G)
B=>C ([COPROG]=E)